

**Progress at UCLA on
Liquid Metal MHD Free Surface Flow Modeling
and Experiments for ALIST**

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PFC/ALPS Meeting
Sandia National Labs, Livermore, USA
December 6-8, 2004



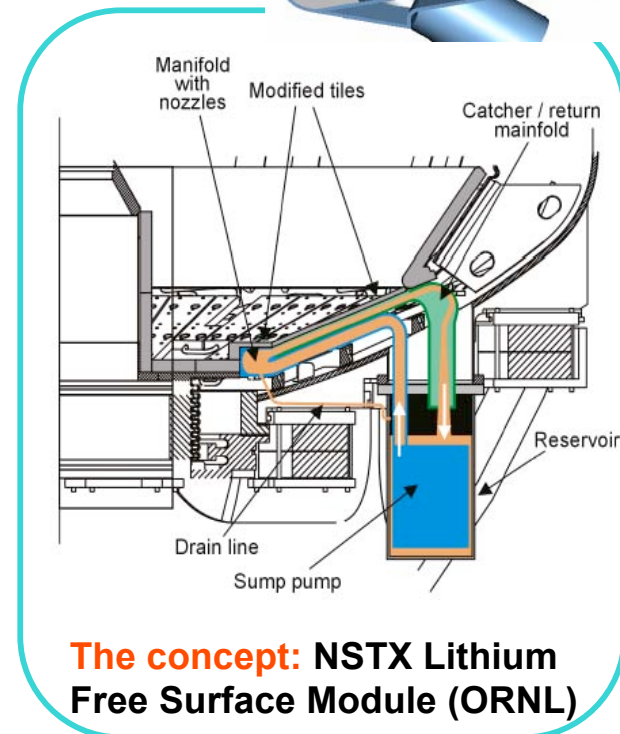
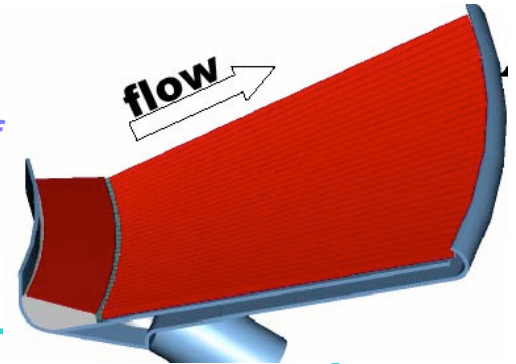
Outline

- Motivation and Strategy
- Recent Work and Results and Tasks
 - Ga-alloy film flow simulations and MTOR experiments
 - Simulations of Lithium jet flow in LIMITS and NSTX fields
- Other Plans for FY2005

MHD flow control issues are a critical for a flowing lithium divertor in NSTX

- ❑ ALIST evolution towards Flowing Lithium Module
 - Module A: thin stagnant liquid Li
 - Module B: flowing lithium
- ❑ Dominant MHD issues potentially leading to flow disruption in Module B.
 - Self generated currents in complex magnetic fields
 - Thermoelectric or halo (other) currents at points of plasma contact
 - Time varying fields: startup

*Sketches of
Li flow
module for
NSTX*



ALIST LM-MHD effort coordinated between UCLA and SNL and utilizes both numerical and experimental approaches

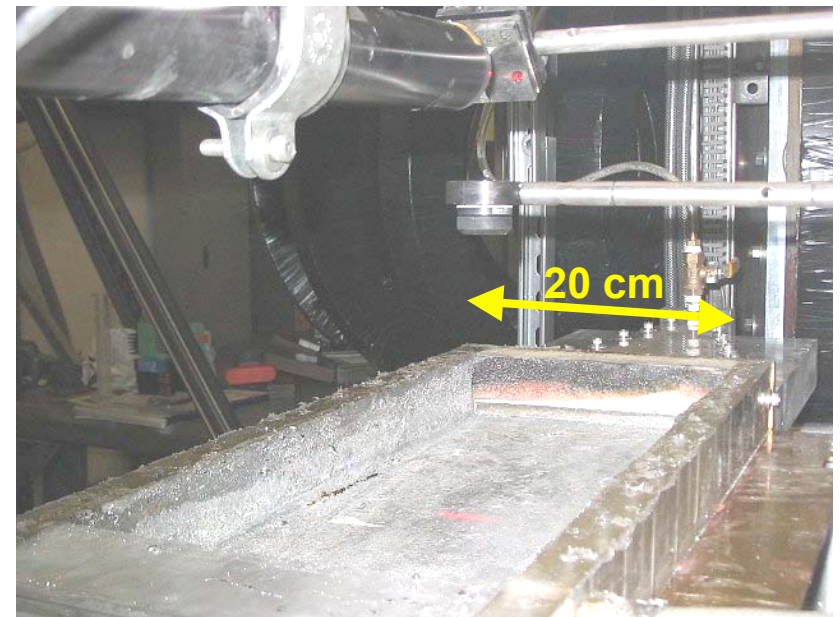
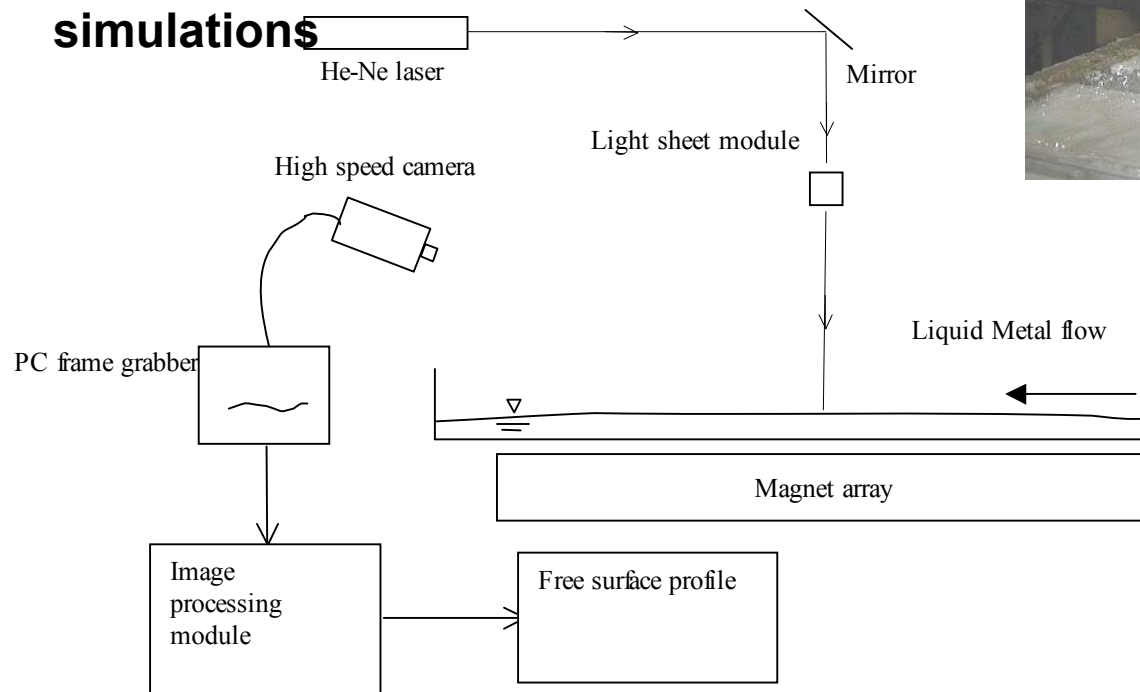
- ❑ Numerical modeling and high-speed parallel computation (UCLA)
 - **HIMAG 3D** free surface MHD code
 - New tools from Metaheuristics?
- ❑ Small laboratory experiments (UCLA and SNL)
 - **MTOR**: currently being used to study “wide” film flows
 - **LIMITS**: will continue investigation of jet flows this year
- ❑ Research Strategy – present a coherent picture to NSTX decision makers
 - Understanding of MHD flow phenomena
 - Gain experience with LM handling and flow systems
 - Choice of best candidate configuration for more detailed design and simulation campaign (formerly planned end of FY05)

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MTOR wide (20cm) LM film flow experiment in a surface normal magnetic field

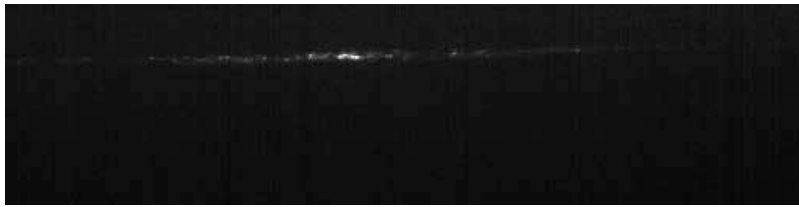
- Surface normal field produced by an array of permanent magnets
- Test section and magnet array will go into reconfigured MTOR for full 3 component field
- Currently, experiments are being run in surface normal field for comparison to simulations



*UCLA - Wide channel
test section and
diagnostic systems*

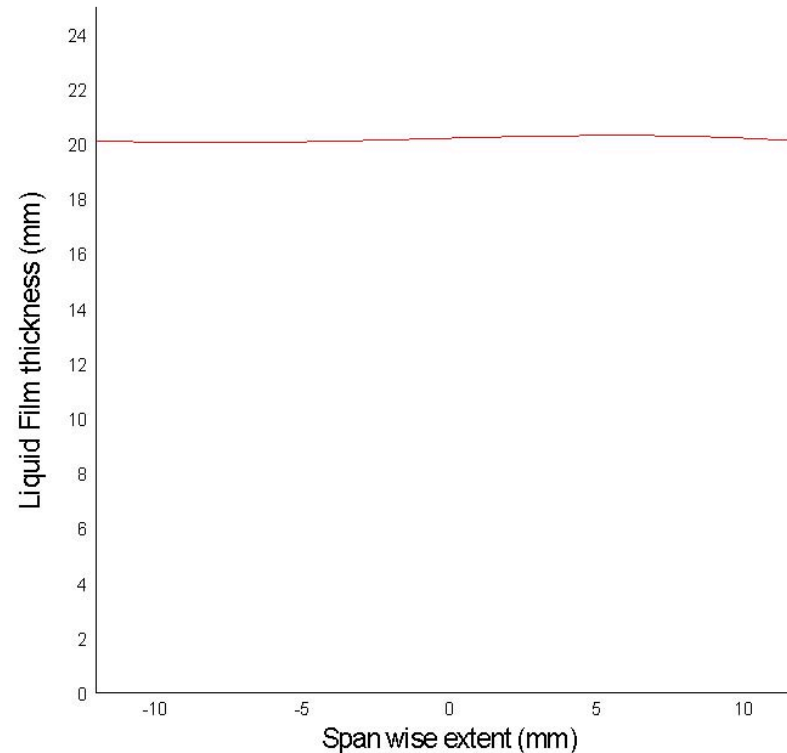
Liquid metal film thickness measurements with scattered laser light sheet

- ❑ Liquid metal film thickness, evaluated 16cm downstream at an average inlet velocity of 1.1m/s.
- ❑ The location is **downstream** of the hydraulic jump for the current inlet velocity.
- ❑ The light beam covers 3 cm width around the channel center.



← 3 cm →

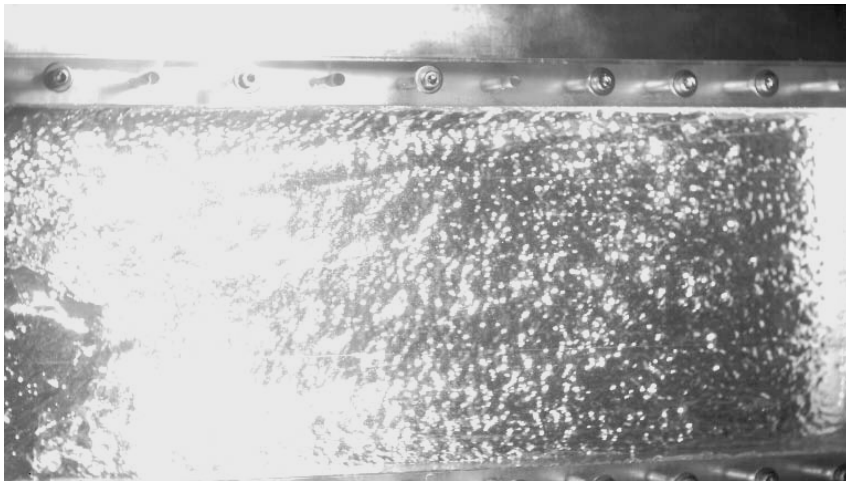
The movie to the right shows 50 frames processed from the one on the left using image processing software.



Initial experimental observations for horizontal LM film flow

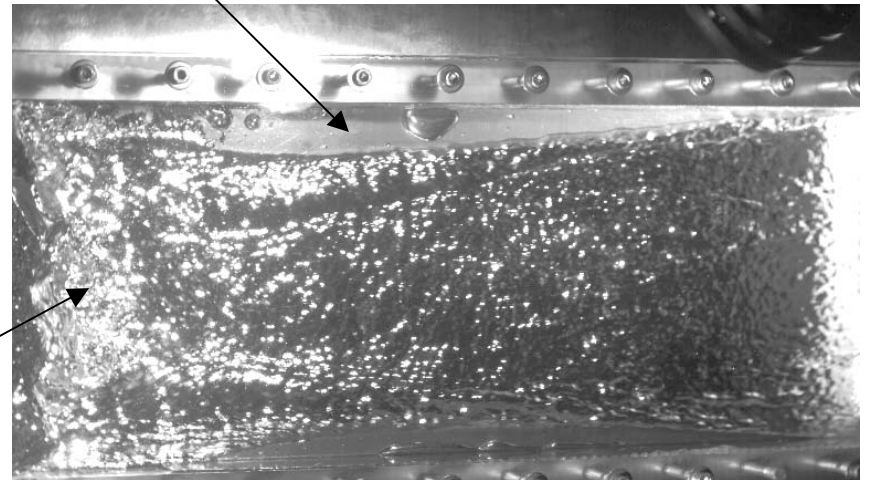
- ❑ At higher inlet velocities ($\sim 2.5 - 3.0 \text{ m/s}$) the liquid metal tends to get pushed inwards from the side walls of the conducting channel, creating separation zones and bare spots.
 - Area contracts to catch less flux in an increasing surface normal magnetic field
- ❑ For horizontal flow, the flow tends to go through a sudden hydraulic jump, located at a particular downstream location, this dissipates a large amount of flow energy and slows down the liquid.
 - The hydraulic jump location moves further downstream as the inlet flow velocity is increased and front changes shape in the span wise direction.

Images of 3 m/s inlet flow with and without magnetic field



Flow at inlet velocity of 3.0 m/s without any applied magnetic field

Liquid pulling off from the walls

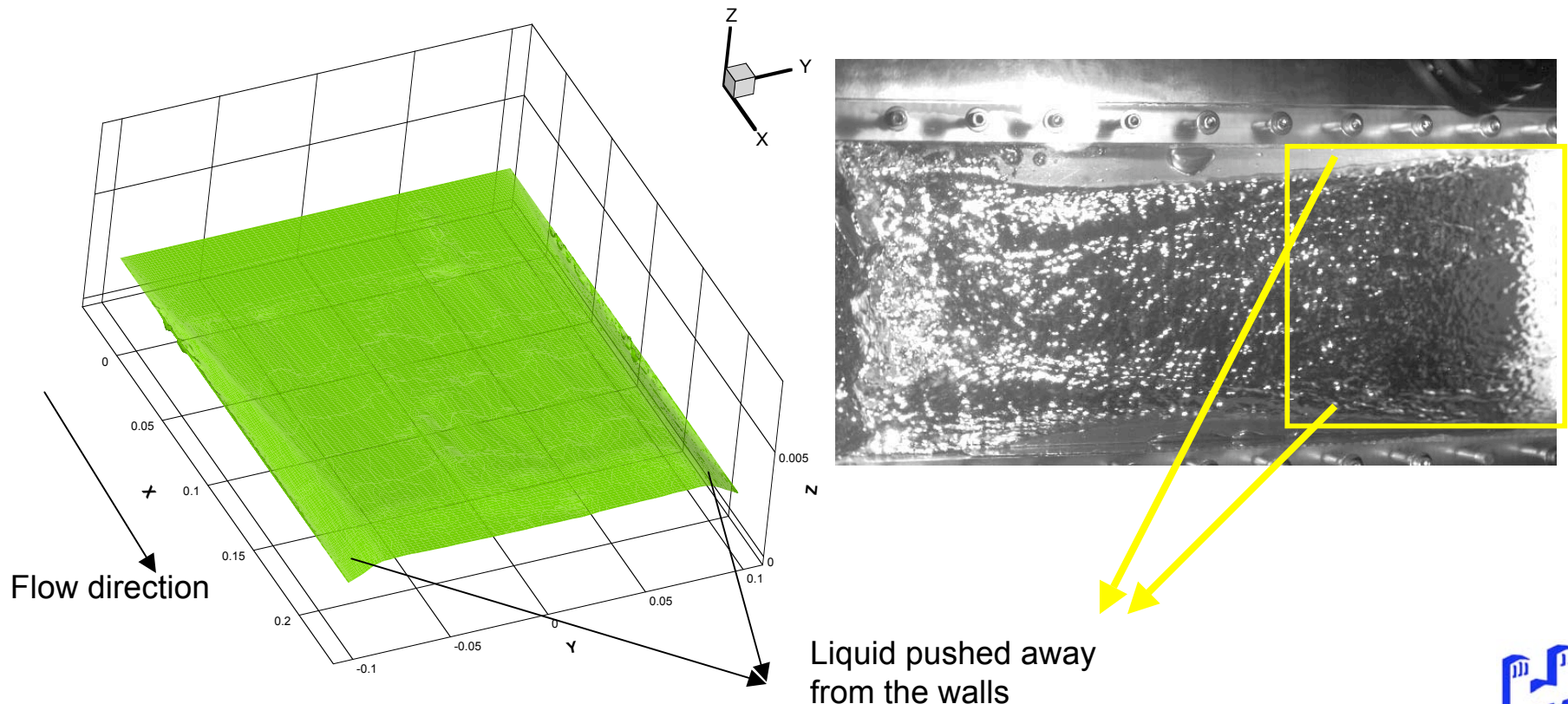


Hydraulic jump

Flow at inlet velocity of 3.0 m/s with the magnetic field

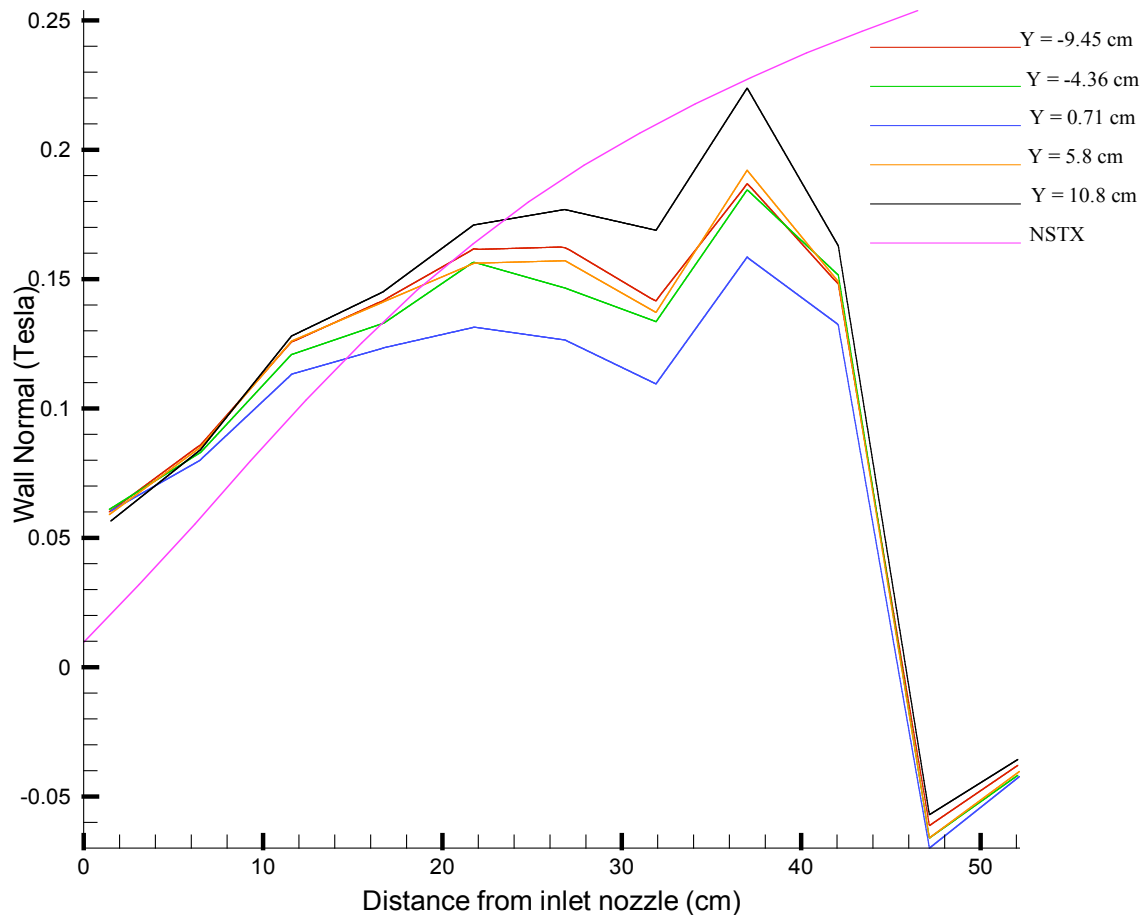
HIMAG SIMULATION, comparison with experiment

- ❑ The increase in film thickness by 1.3 mm at 16cm downstream for an inlet velocity of 3m/s, predicted by HIMAG compares well with that observed experimentally. (Experimental value shows an increase of 1.5mm at 16cm downstream for an inlet velocity of 2.5m/s)
- ❑ Experiments show the liquid being pushed away from the walls at inlet velocities (2.5-3m/s), the same tendency is observed in the numerical simulation.



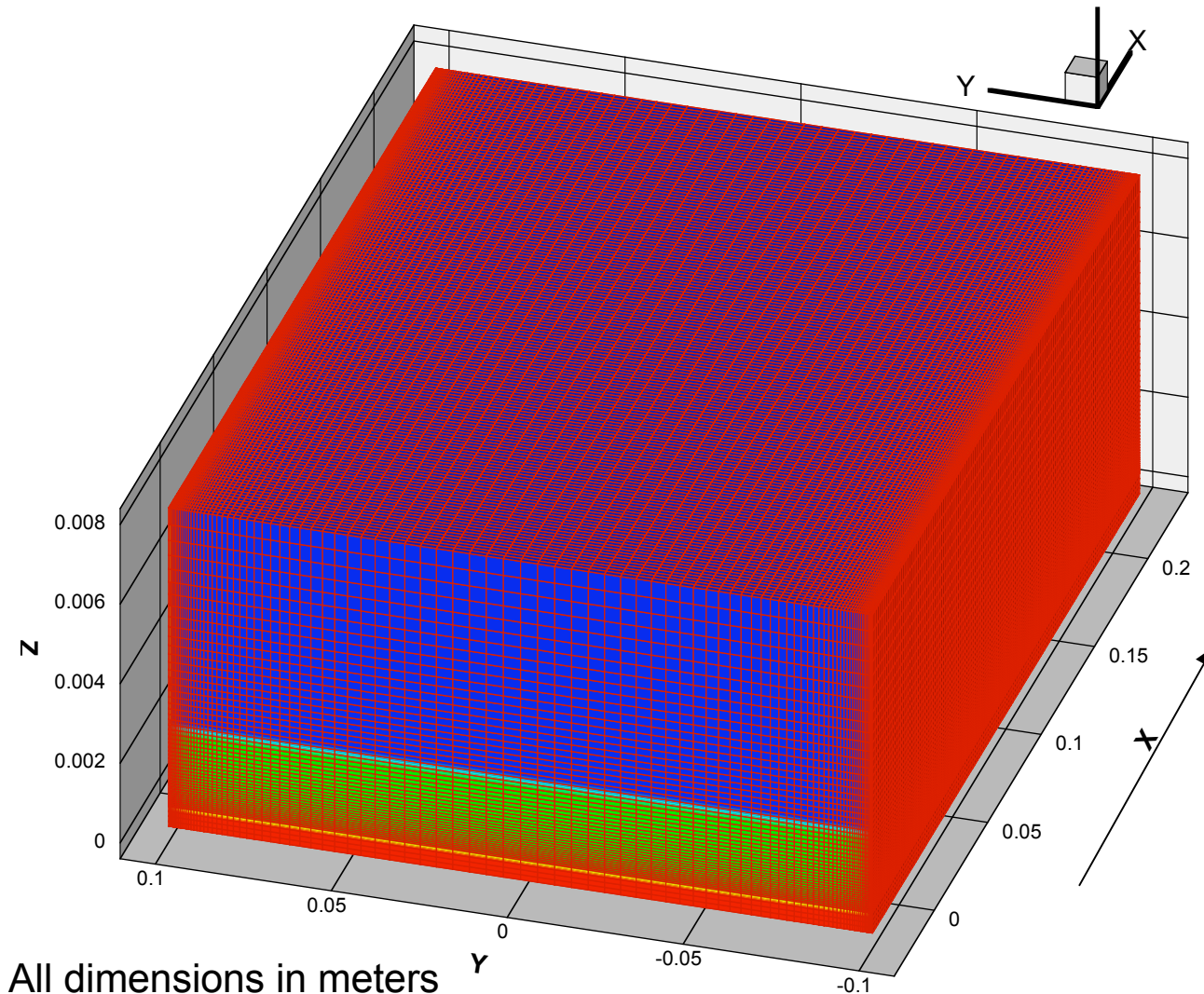
Some Problem with the Applied Magnetic Field

An assortment of permanent magnets placed beneath the test section are used to reproduce the scaled NSTX divertor region wall normal magnetic field component



- The stream wise variation of the magnetic field is measured at five different span wise locations. 'Y=0.0' marks the center of the channel
- Only first 20 cm of flow is "accurately" reproduced
- New array has been designed and will be assembled in upcoming weeks

The entire computational domain (divided on 8 processors). 'X' represents the flow direction, 'Y' is the span. The plot has been stretched in the 'Z' direction for clarity.



The computational domain has 880000 cells.

Only the first half of the channel length, in the stream wise direction is simulated.

The green part represents liquid gallium and the blue part argon. The inlet face can be seen in the figure.

All dimensions in meters

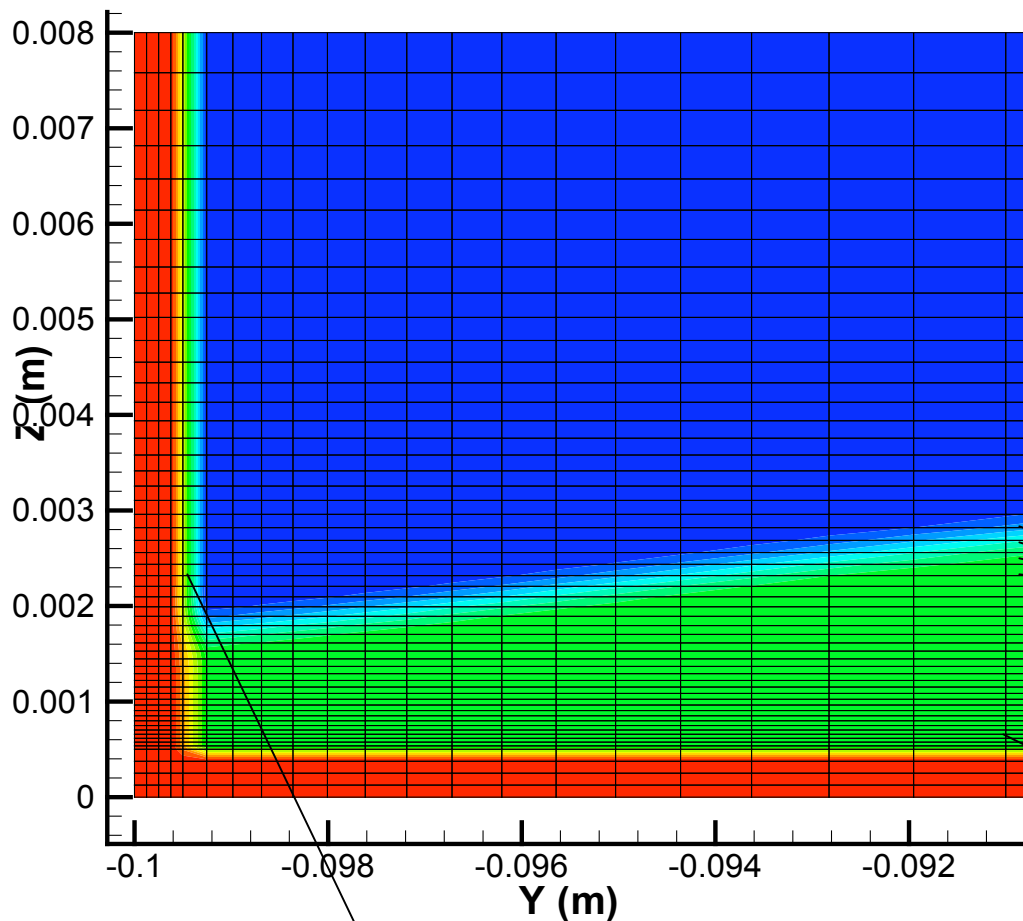
Y-Z cross section cut at 16cm downstream from the inlet nozzle. The cells are shaded according to density.

The liquid is coming out of the plane. Vertical axis represents thickness and horizontal the span.

Blue represents argon. Green represents liquid gallium and Red represents the stainless steel solid cells.

The interface is diffused over four cells by using the heaviside function.

Grid stretching to resolve the Hartmann layer which is of the order of 250 micron.



Grid stretching near the side walls

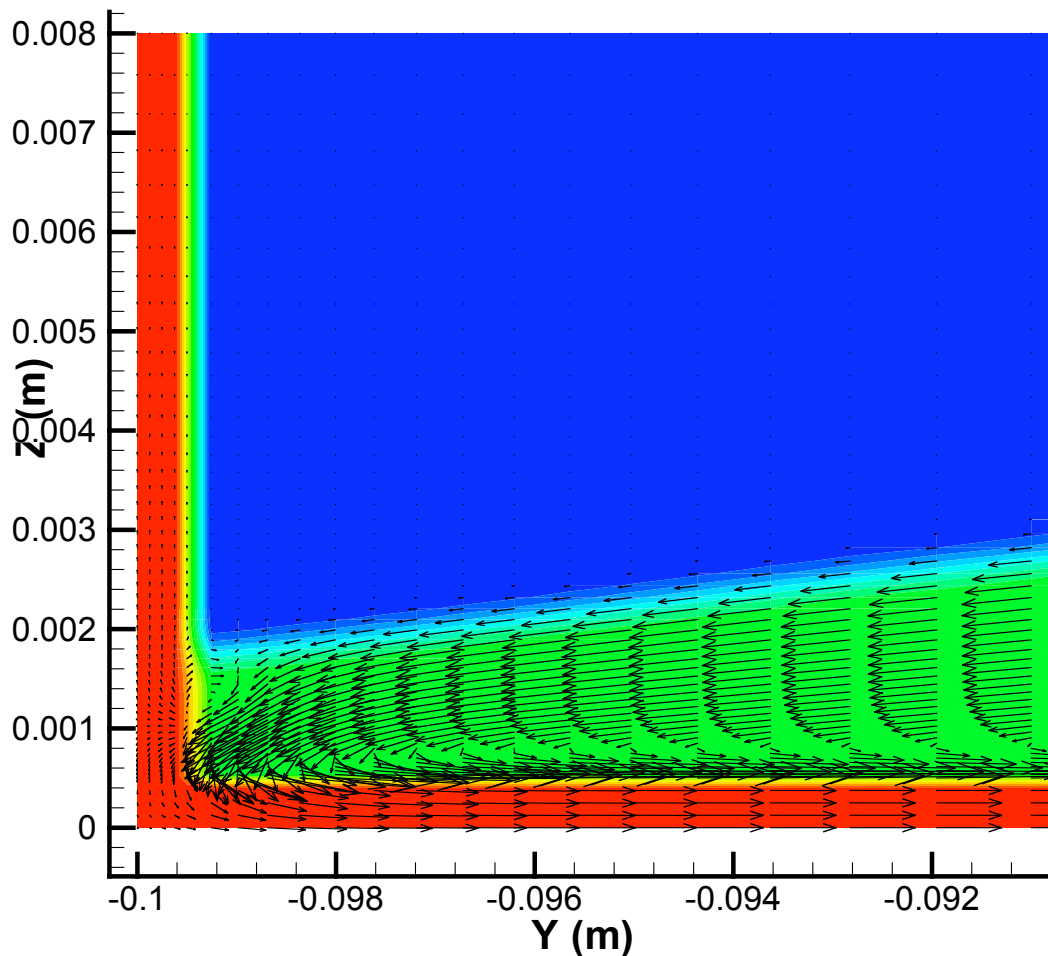
Y-Z cross section cut at 16cm downstream from the inlet nozzle. The cells are shaded according to density.

Induced currents in the Y-Z plane. J_y is the strongest induced current component.

The liquid is coming out of the plane. Vertical axis represents thickness and horizontal the span. The dominant magnetic field points in the 'Z' direction

Electrical conductivity of gallium is three times that of stainless steel.

Return current path through the Hartmann layer

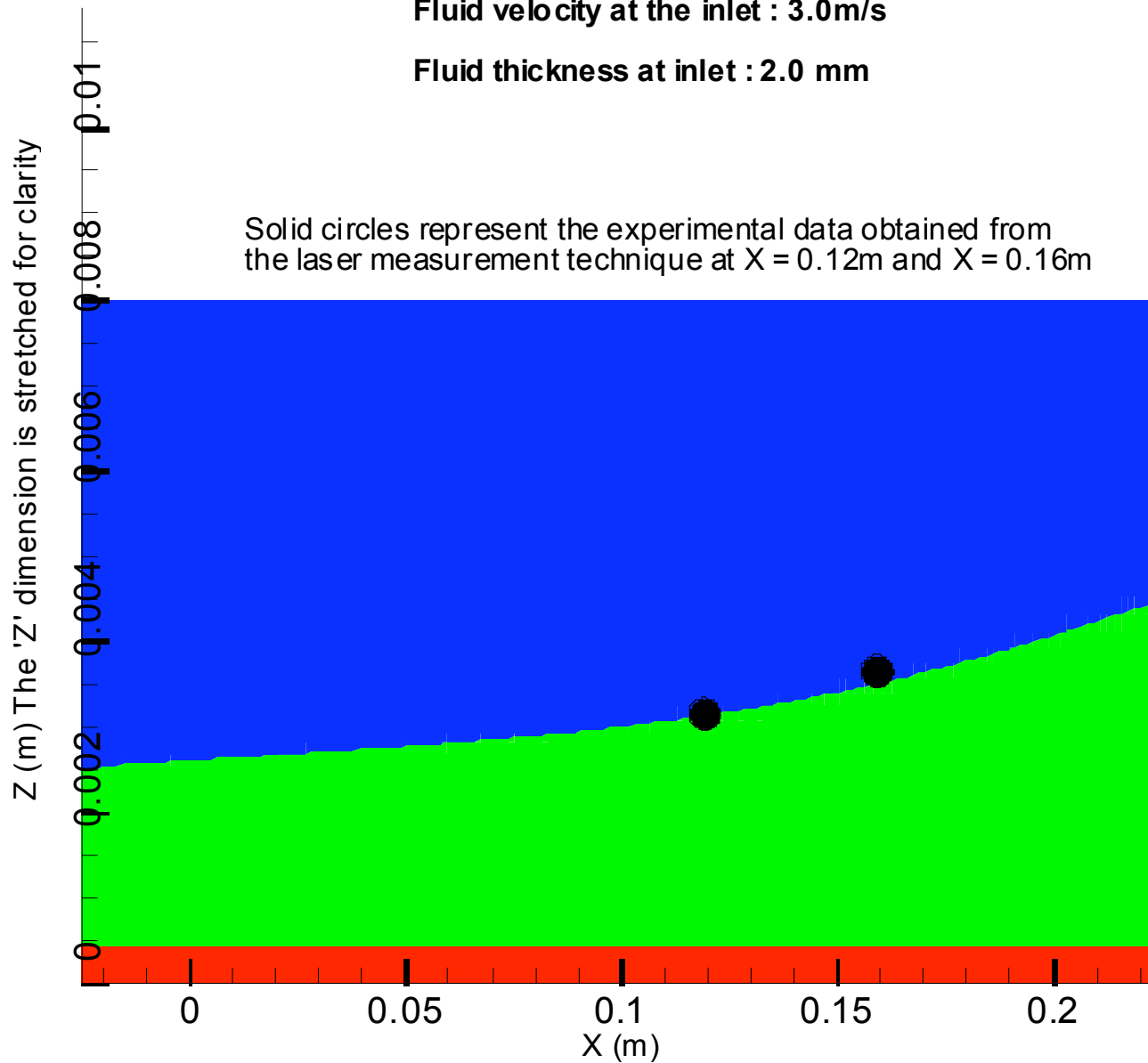


The stream-wise variation of fluid film thickness

Section extracted from the channel center ($Y = 0.0\text{m}$)

Fluid velocity at the inlet : 3.0m/s

Fluid thickness at inlet : 2.0 mm



Experimental Values

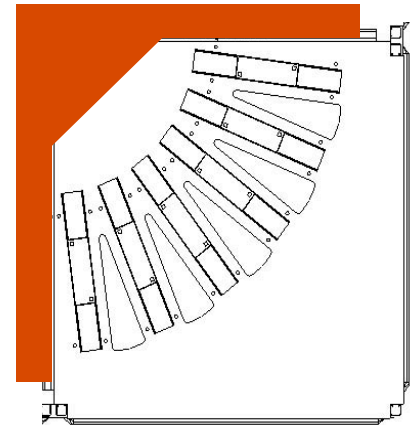
$X = 0.12\text{m}$, $\Delta h = 0.645\text{ mm}$

$X = 0.16\text{m}$, $\Delta h = 1.3\text{ mm}$

Tasks this year for improved film flow experiments

- ☐ Better surface normal magnetic field built from permanent magnets (no iron)
- ☐ Addition of toroidal field $\sim 1\text{T}$. Requires reconfiguration of MTOR
- ☐ More quantitative data on surface height and velocity over more surface points

3800 A in
6 28-turn coils



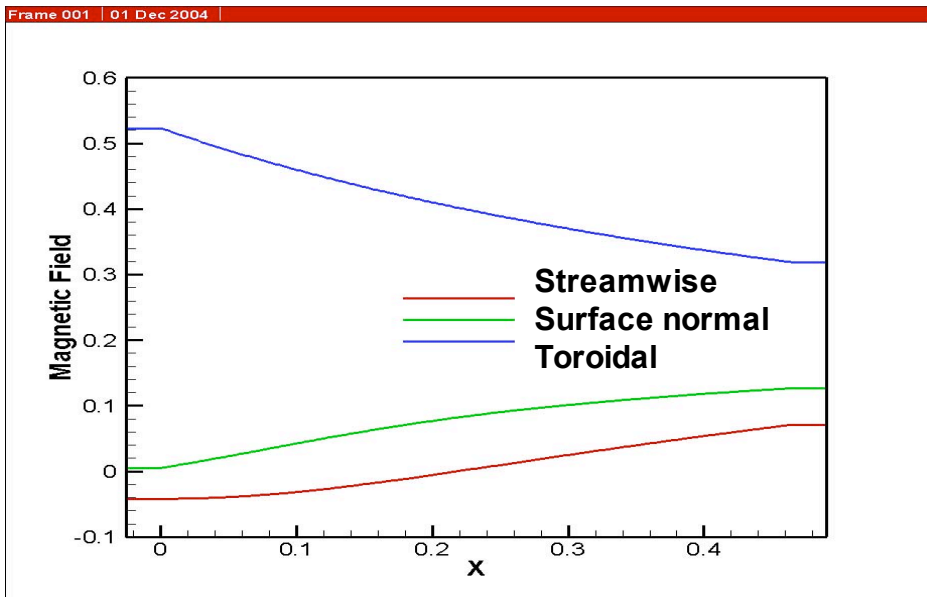
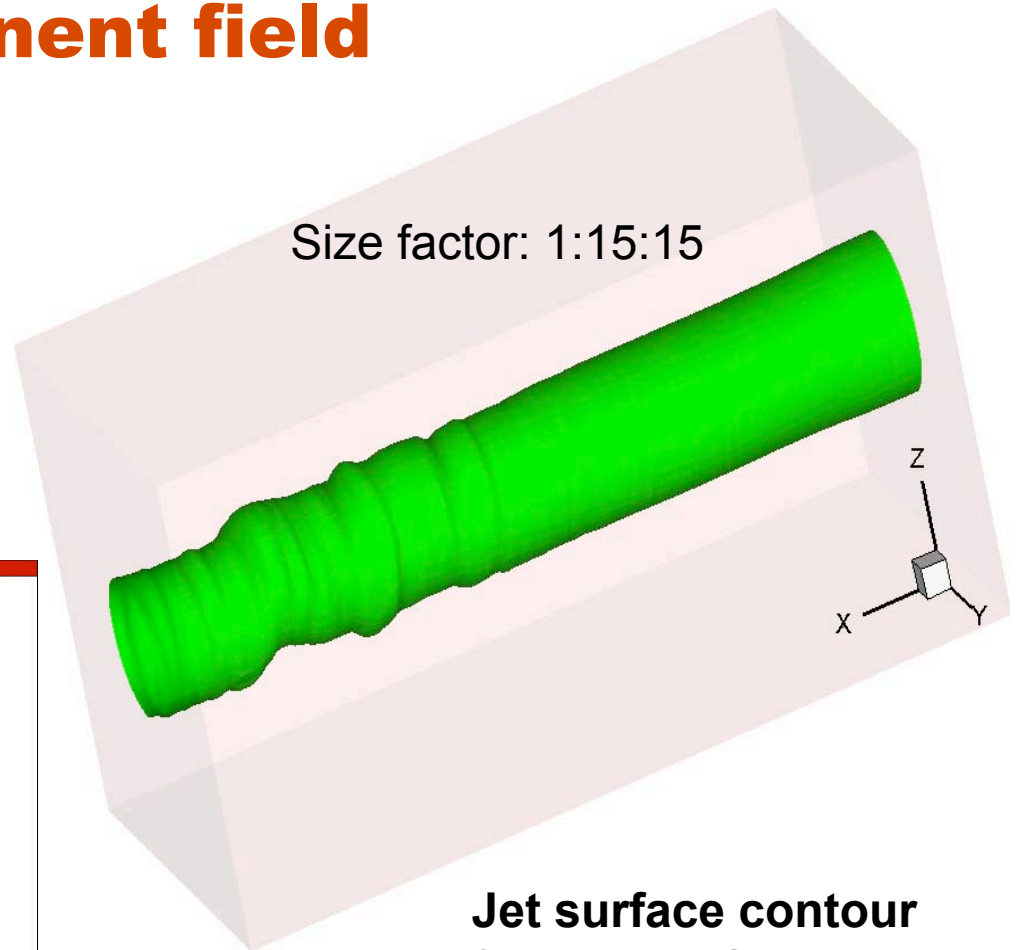
MTOR Top View

Outline

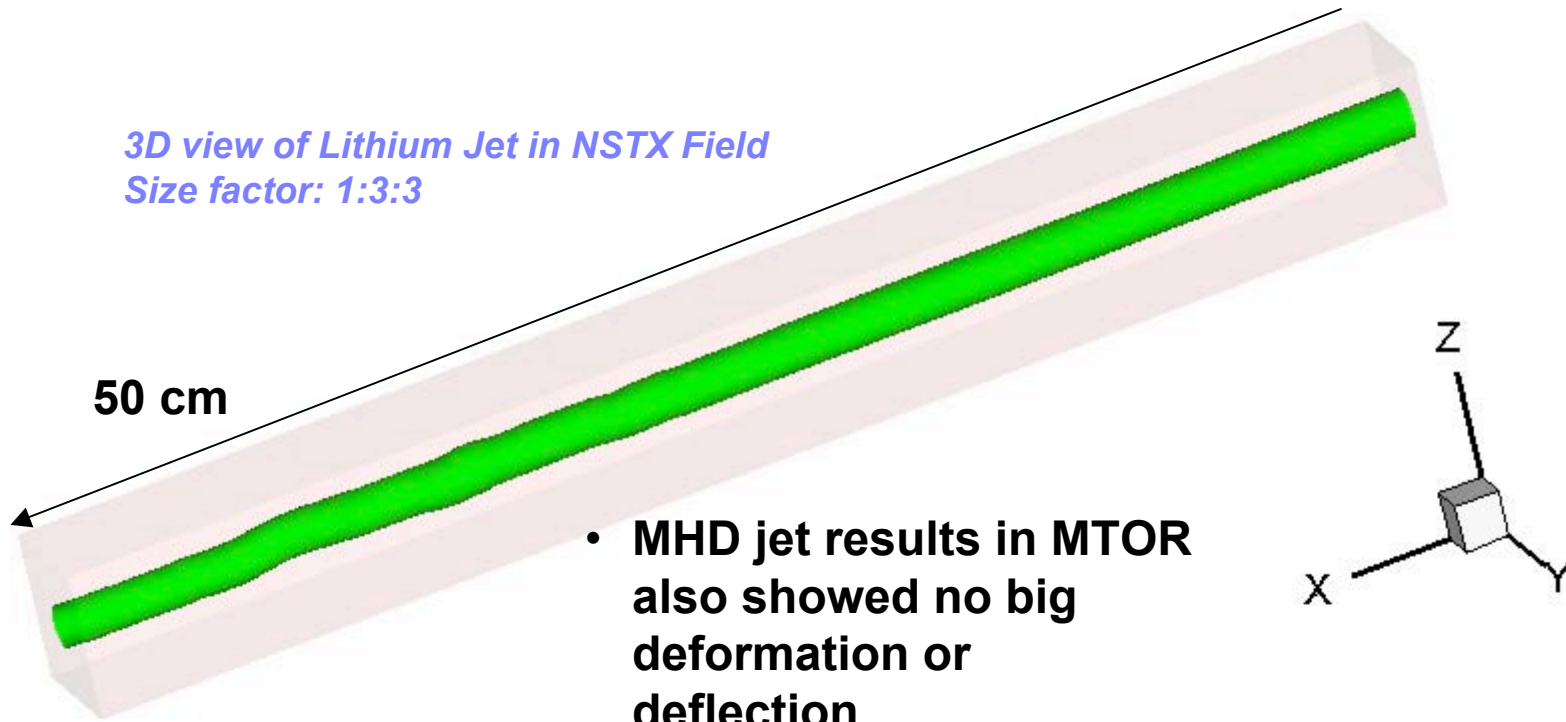
- ❑ Motivation and Strategy
- ❑ Recent Work and Results and Tasks
 - ❑ Ga-alloy film flow simulations and MTOR experiments
 - ❑ **Simulations of Lithium jet flow in NSTX and LIMITS fields**
- ❑ Other Plans for FY2005

Jet ripples and wanders slightly, but no significant deformation in NSTX 3 component field

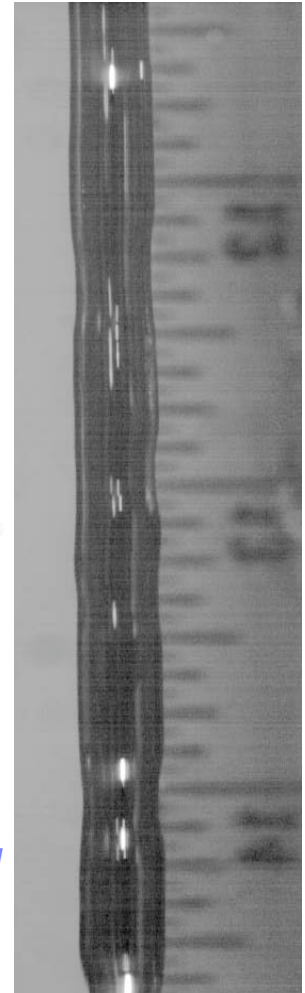
- ☐ Lithium properties
- ☐ 10 m/s inlet velocity
- ☐ No inlet nozzle
- ☐ No perturbation inlet condition
- ☐ 3 component magnetic field



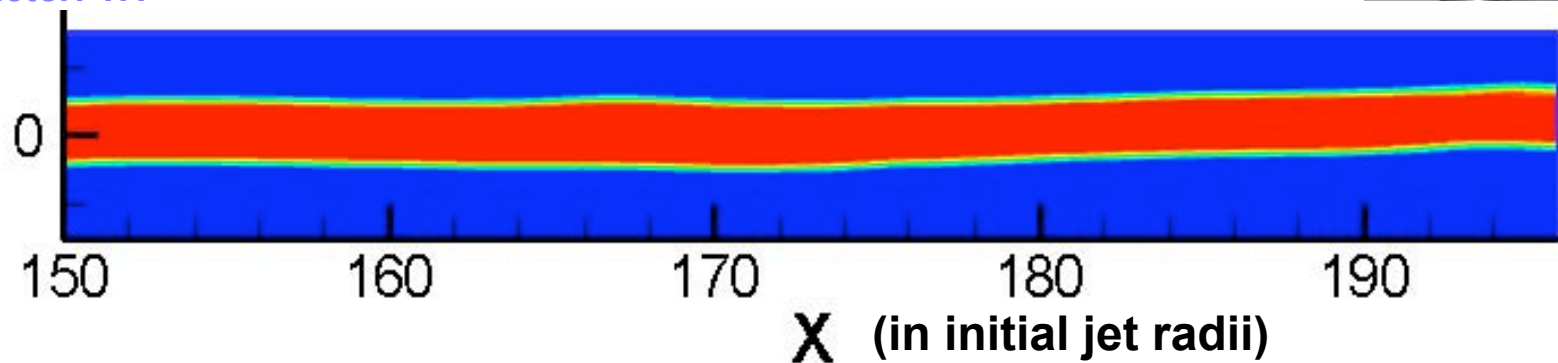
3D view of Lithium Jet in NSTX Field
Size factor: 1:3:3



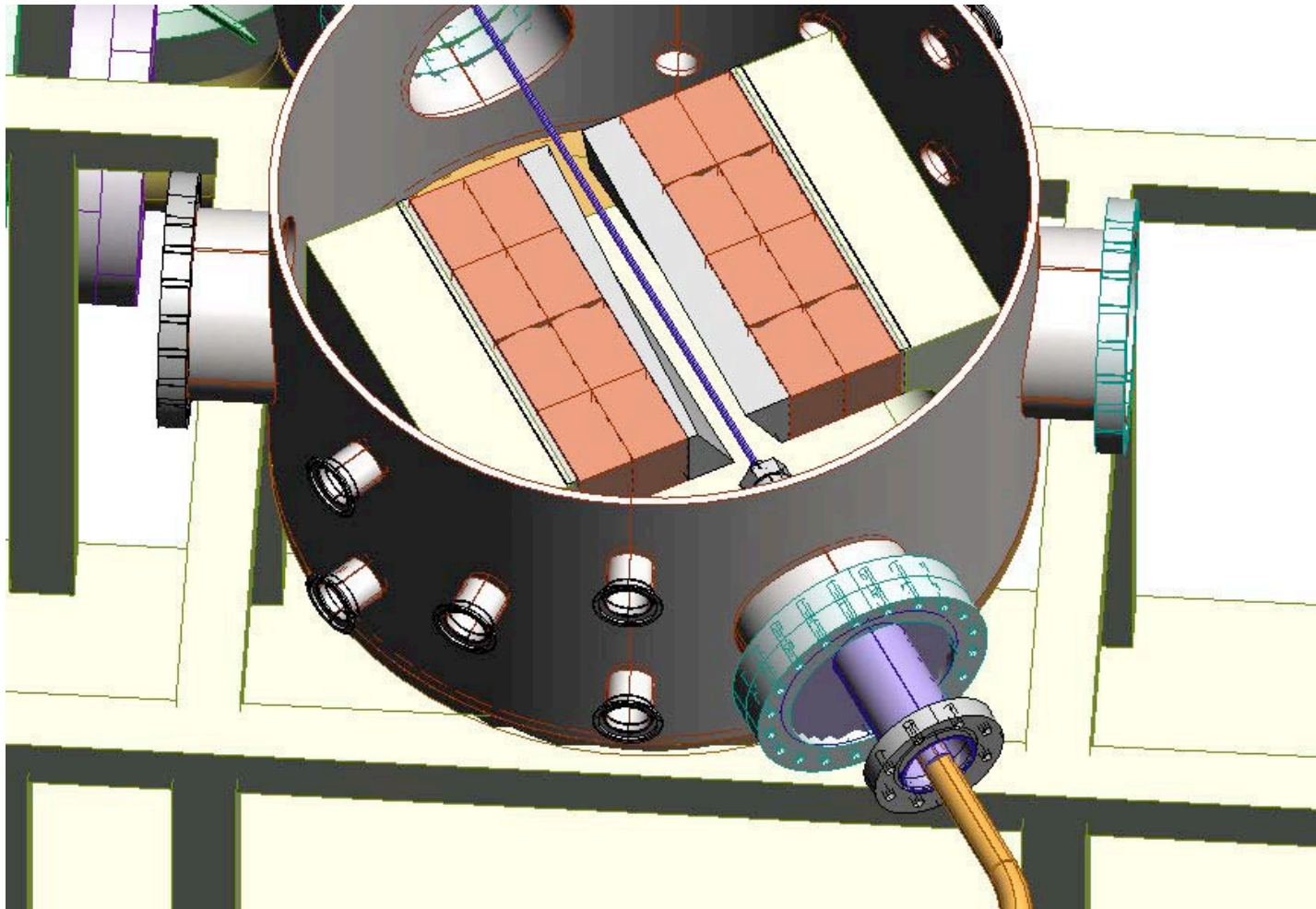
Ga alloy Jet flows in MTOR under increasing field strength



2D cross section of Lithium Jet in NSTX Field
Size factor: 1:1

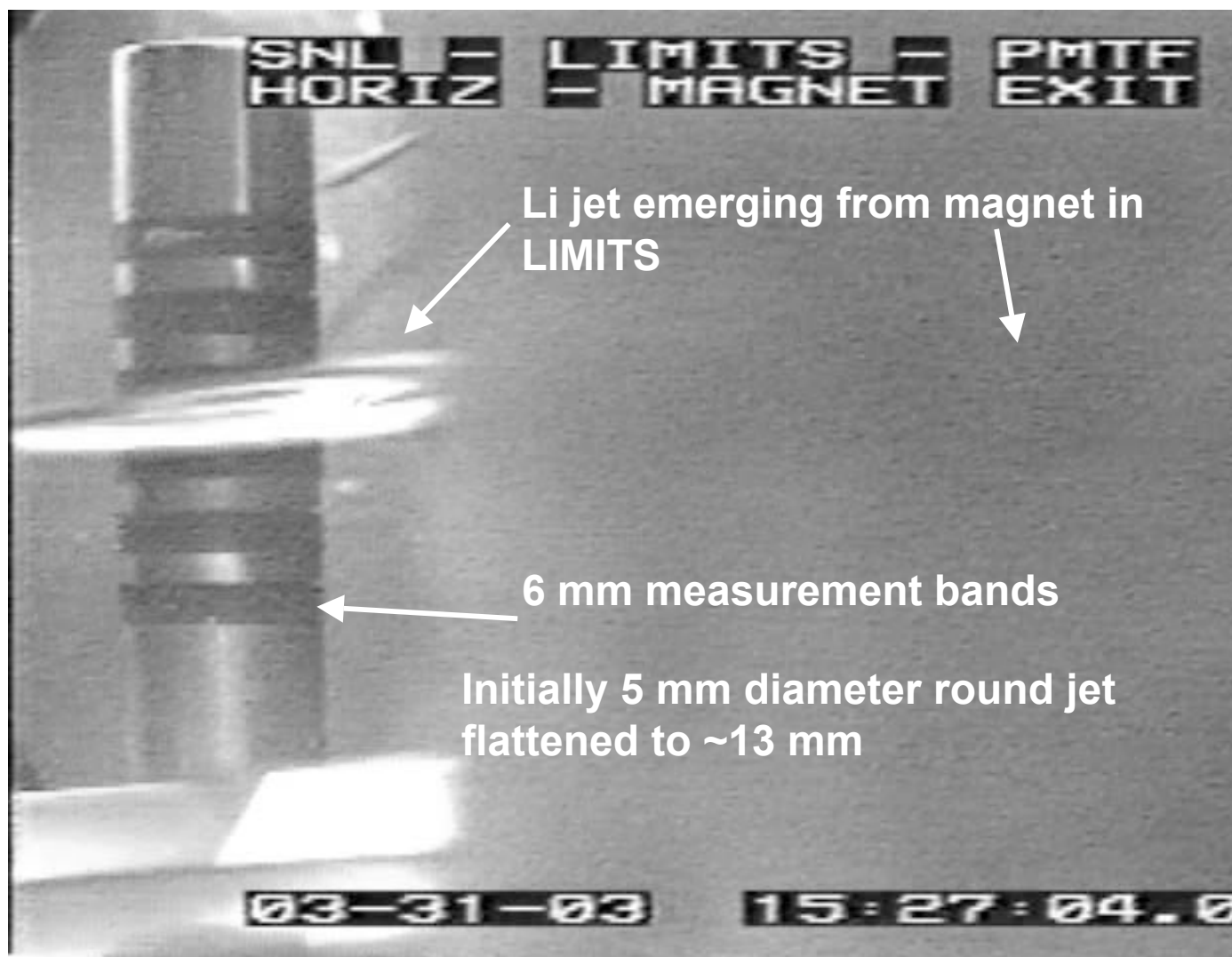


**Lithium flow in LIMITS is from
weak to strong field
(outboard to inboard in NSTX)**

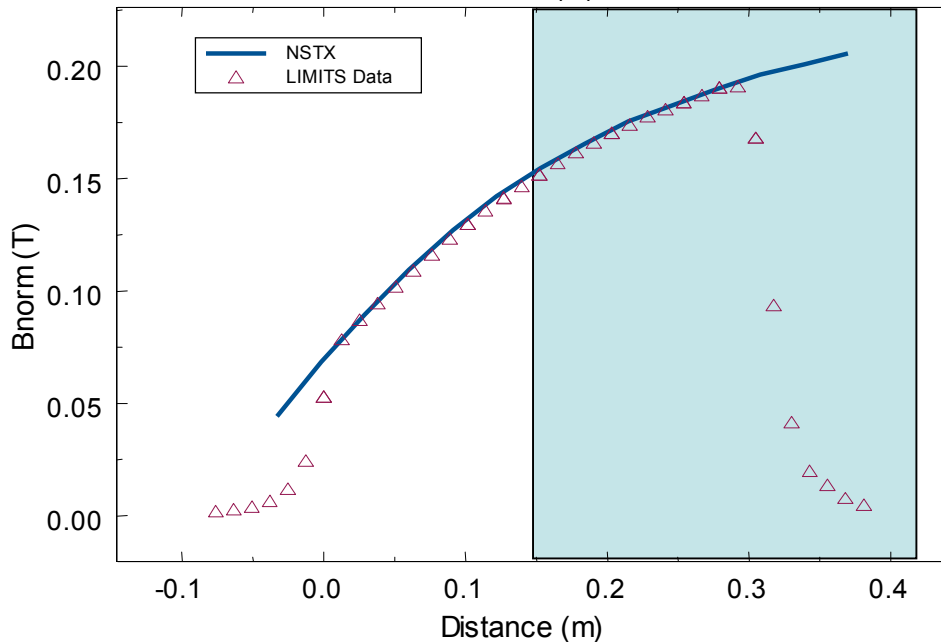
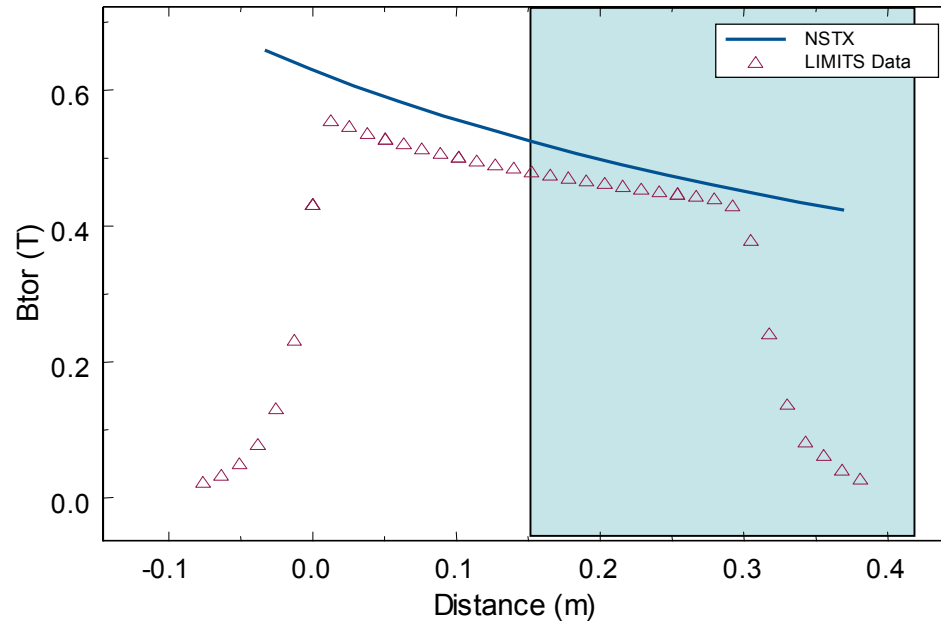


See Tanaka, Special APEX issue of *FED*, 2004


LIMITS Jet flattened as it emerges from the magnet gap



LIMITS Exit Field Simulation



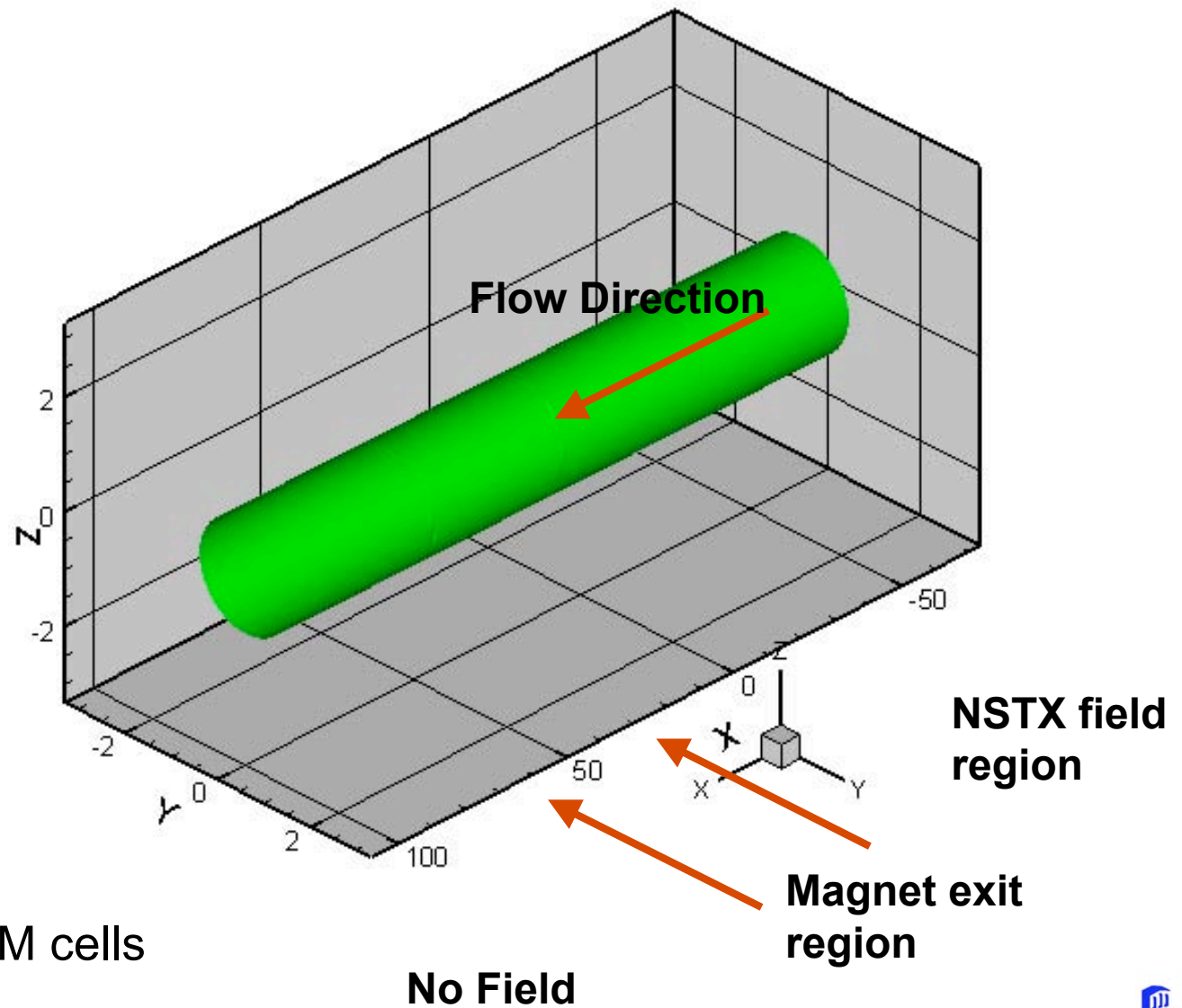
- ☐ Jet flows initiated in the magnet with round cross-section near the field exit region
- ☐ Increased viscosity 4x used
- ☐ Different initiation strategies tried (A) abrupt turn-on and (B) gradual turn-on with extra damping

 Calculation area
In this presentation

Limits Magnet Exit

4x viscosity

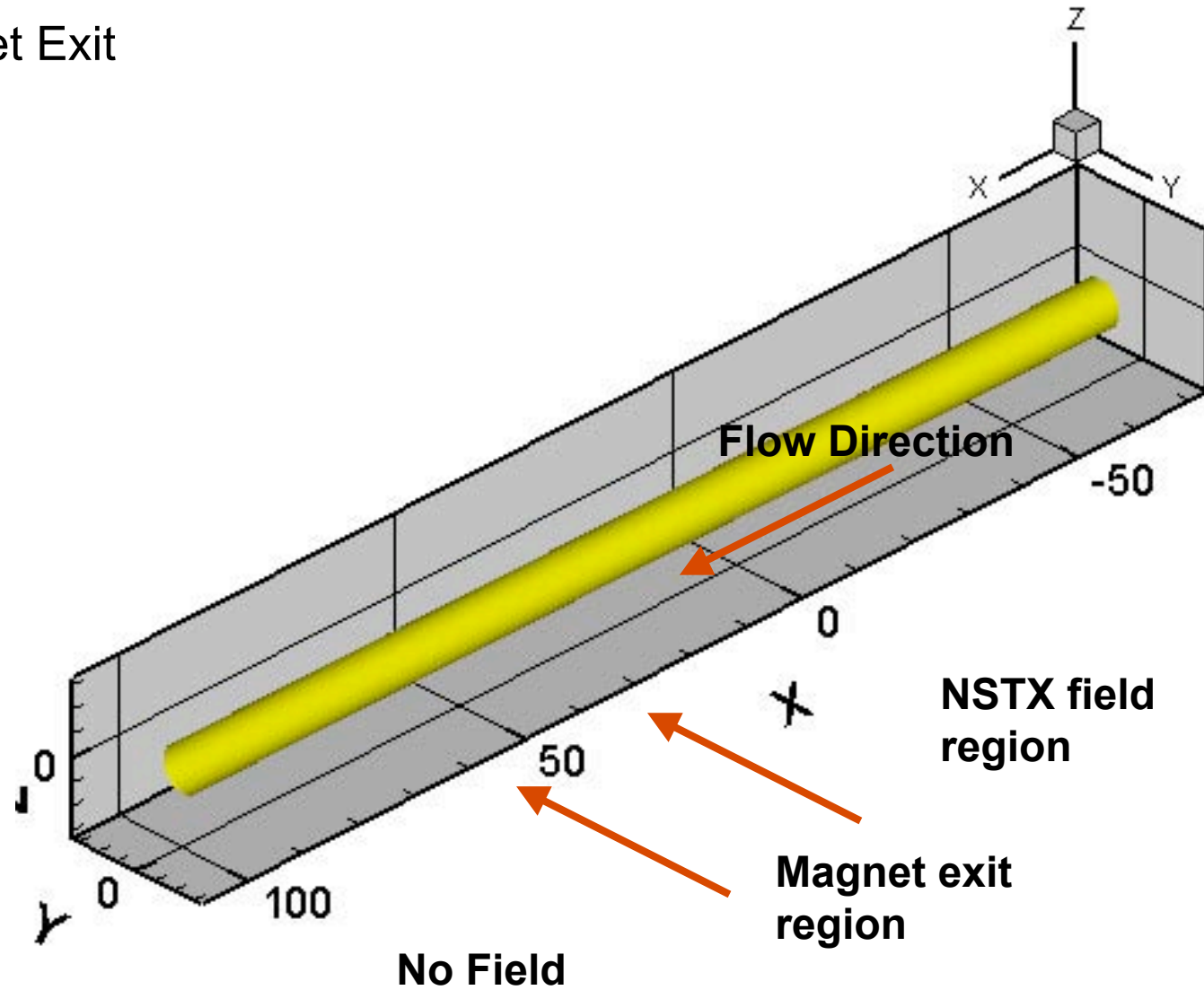
abrupt start



Grid 370x75x75, >2M cells

Magnification 1:15:15

Limits Magnet Exit
4 x viscosity
Abrupt start

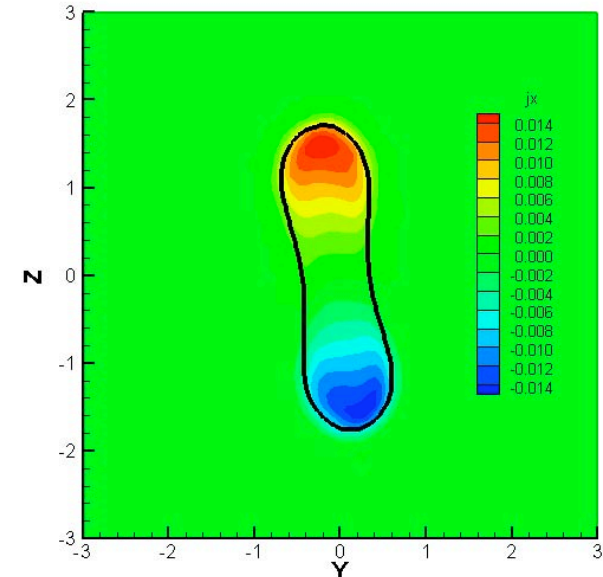
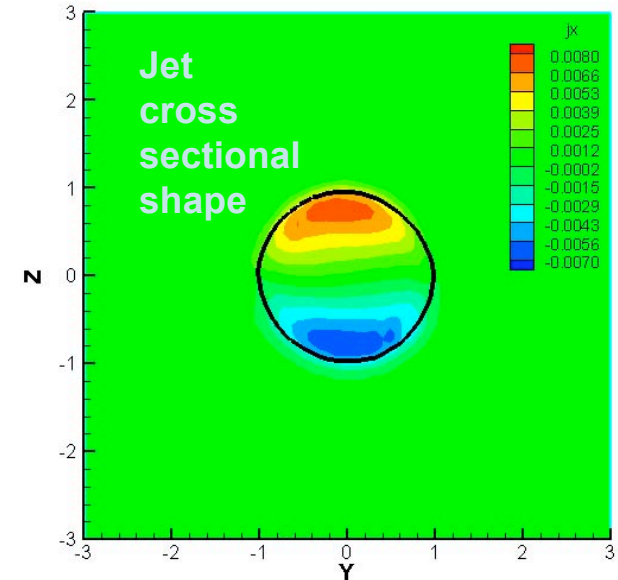
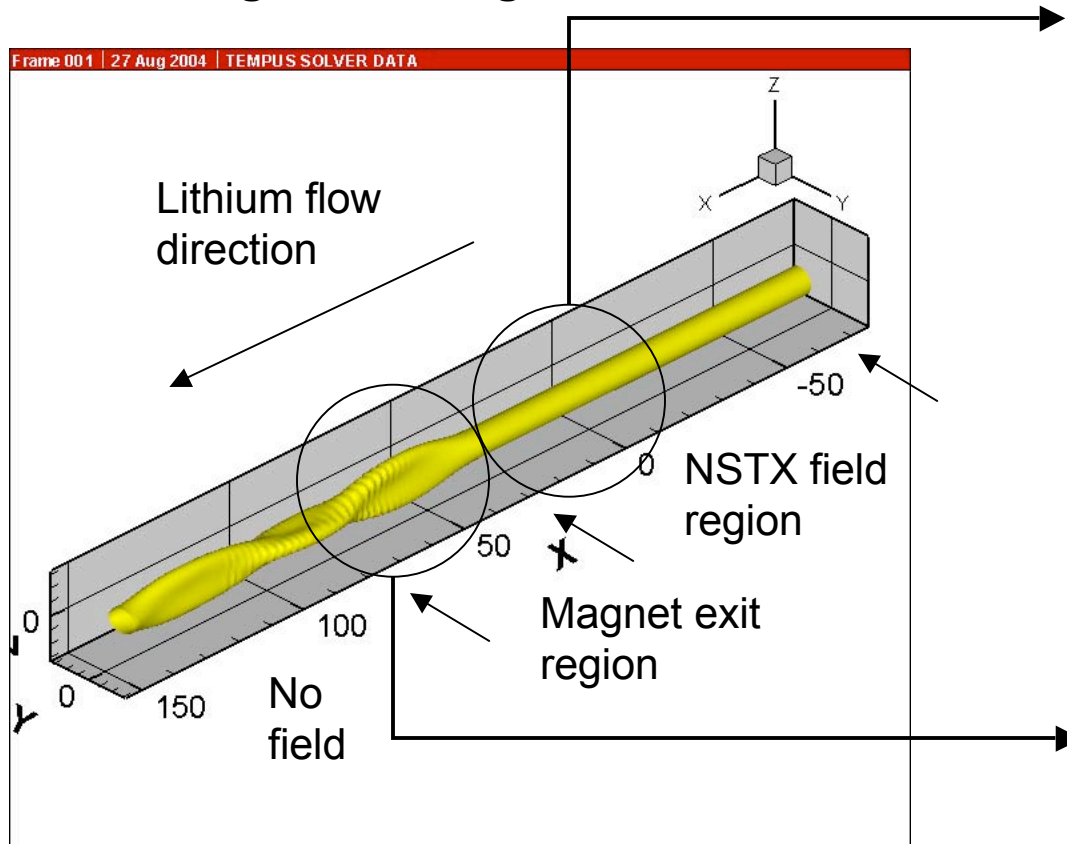


Grid 370x75x75

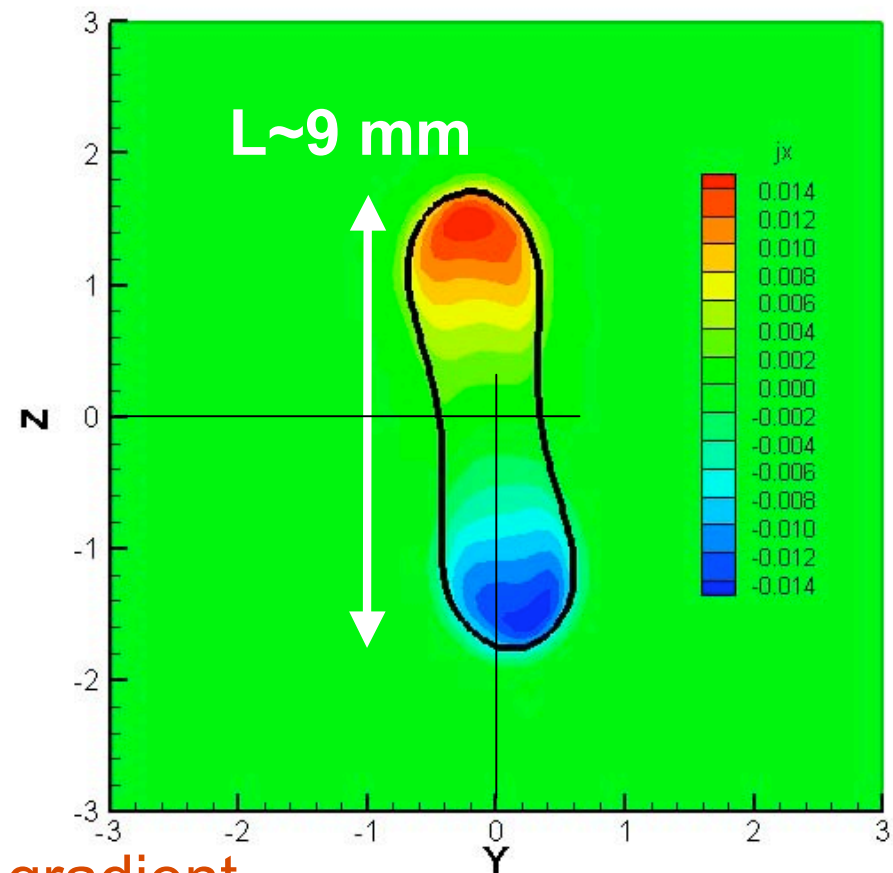
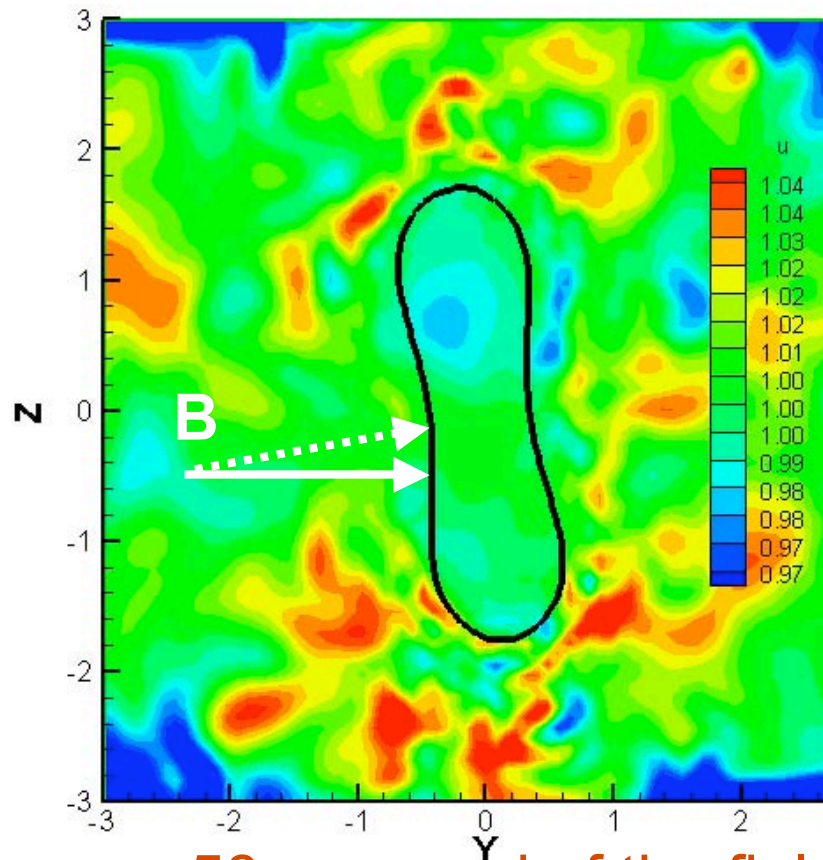
Magnification 1:3:3

First 3D MHD Simulation of lithium jet flow with LIMITS experiment parameters

- ❑ No deformation in prototypic NSTX-like magnet field region – good news for NSTX module
- ❑ Strong deformation seen only in high gradient LIMITS magnet exit region



Cross section of maximum deformation less than observed deformation in **LIMITS** experiment



$x=58$ near end of the field gradient,
 $t=78$ ms greater than 2 flow-thru times

Summary and future of LM-MHD jet simulation

- ❑ Initial results for NSTX case with strong-to-weak-field flow direction and jet initiation in the field region shows no significant deformation
- ❑ Large deformation seen in LIMITS comes from magnet inlet and outlet gradient fields.
 - Reason for change of state from deformed to almost non-deformed steady state is uncertain
- ❑ Effects of conducting nozzles and common manifolds likely to be important and must still be modeled
- ❑ Effects of plasma contact must still be modeled

UCLA Tasks in FY 2005

Work in FY05 will focus on the following MHD Simulation tasks

- ❑ **Improving the high Reynolds number capability of 3D-HIMAG** with least squares velocity interpolation, higher order upwind scheme, higher resolution and problem sizes.
- ❑ **Simulations of wide film and jet flows in NSTX 3D fields, continuing MTOR experiments.** Simulations will continue in increasingly complex magnetic fields and the presence of conducting structures.
- ❑ **Simulations of ultra-thin film layers with specified plasma current scenario.** Evaluation of likely maximum thickness before plasma current driven motion might disrupt the film flow and cause lithium mobilization in the NSTX chamber.

2005 Experimental simulations in MTOR focus on producing data useful for validation of codes and exploring geometries and conditions not easily modeled

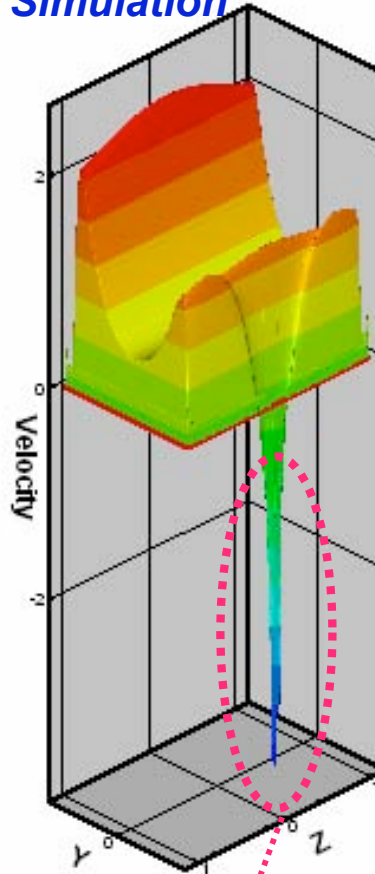
- ❑ Higher field 1/4 MTOR section for better NSTX field and ITER TBM simulation conditions.** Higher coil current and improved cooling/bracing will be required on the 6 coils.
- ❑ Wide channel LM flow in surface normal field.**
 - The field constructed by permanent magnets will be improved for a greater portion of the flow length.
 - Wide channel LM flow in toroidal and normal magnetic fields will be introduced into the higher field MTOR sector to investigate the combined effect of wide film flow (20 cm) in conducting structures in NSTX like magnetic fields and field gradients.
- ❑ Design of NSTX experimental plan together with SNL, PPPL and other interested parties**

Complex geometry MHD codes already being applied to DCLL blanket with SiC

Flow Channel Inserts

- ❑ 2D and 3D codes (developed for Liquid walls) have been modified for DCLL
- ❑ Initial results show strong sidelay jets at $\sigma_{\text{SiC}} = 500$ S/m with current DCLL design
- ❑ 2D and 3D codes give conflicting results concerning flow in the “stagnant” gap region.
- ❑ Code improvements and debugging, and continued simulations planned for FY05.

*Velocity profile from
2D Simulation*



*Strong negative flow jet near pressure
equalization slot not seen in 3D simulation*

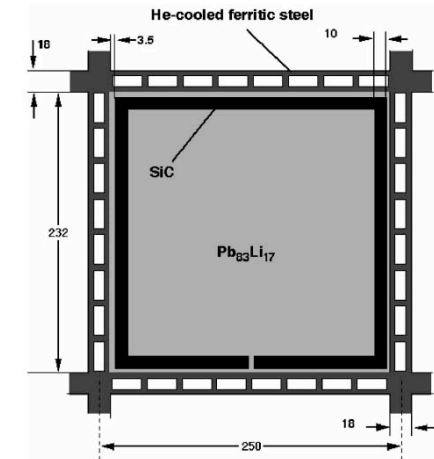
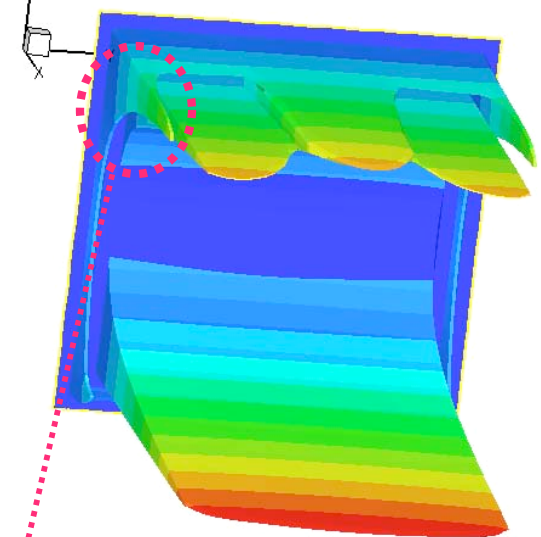


Fig. 8. Cross section of the breeder region unit cell.

Slice from 3D Simulation



*Gap corner
jets not seen in 2D simulation*